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1975 EPA - U.S. HVMA Correlation Study

by
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Standards Development and Support Branch
Emission Control Technology Division
Office of Mobile Source Air Pollution Control
Office of Air and Waste Management
Environmental Protection Agency

June, 1975

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The difference in CO_2 measurements between test sites is believed to be primarily due to a difference in dynamometer characteristics. Two different types of dynamometers (belt-driven inertia wheels and direct-drive inertia wheels) were used in the test. Dynamometer torque measurements revealed that the belt-driven type produced an average of 6% higher vehicle positive torque than the direct-drive type.

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1. Introduction

In 1974, an exhaust emission correlation study was conducted between EPA and the Motor Vehicle Manufacturers Association of the United States, Inc. (MVMA). As a result of that test program it was decided that another, but somewhat more limited study, should be conducted in early 1975.

This report is a discussion of the 1975 EPA-MVMA correlation program. Test data was collected in January, 1975. Participants in the study, and their designation code which will be used in this report, are listed below:

A = American Motors
C = Chrysler
E = EPA
F = Ford
G = General Motors

2. Technical Discussion

2.1 Program Objective

The purpose of this study is to compare the results of vehicle exhaust emission and fuel consumption tests at EPA facilities and several American MVMA members. In addition to comparing test results, this study also compares test equipment, procedures and conditions used at each facility. If there are any real differences in emissions and/or fuel consumption measurement, it is hopeful that the analysis of equipment, procedures, and conditions will reveal the cause of these differences.

2.2 Facilities and Equipment

2.2.1 Test Sites

One test cell, designated as the "master cell", was used at each of the five test sites. The equipment within each test cell was identical to the equipment used in the 1974 correlation study, except for site E's CVS unit. Site E used a positive displacement pump CVS in 1974, but a Philco Critical Flow Venture (CFV) unit was used in the 1975 program.

As in 1974, the major difference in equipment between facilities was dynamometer type. Sites C, E and G used dynamometers with direct-drive inertia wheels and sites A and F used dynamometers with belt-driven inertia wheels.

2.2.2 Test Vehicle

One test vehicle was used in this study. It was a GM car (Repco 1) with 350 CID engine and an inertia testing weight of 4500 lbs. It had engine modification exhaust emission controls and had been further modified to improve hot-start repeatability. Hot-start exhaust emission levels of the vehicle were near the 1975 Federal standards. The test car was also equipped with a rear wheel torquemeter for the measurement of dynamometer torque.

2.3 Program Design

The program was designed to consist of 5 rounds of testing. Each round consisted of 5 days of testing (one day at each facility). Each day four identical tests were conducted. Consequently the test design was eight tests at each site. This test design is shown in Table 1. As shown in the table, only seven tests were actually made at test site A and B because of problems encountered during testing.

2.4 Test Procedure

2.4.1 Vehicle Preparation

Each day, prior to testing, the vehicle was warmed up by driving one LA-4 cycle and 5 minutes of 50 mph steady-state operation.

2.4.2 Emission Tests

After vehicle warm-up, four hot-start 1975 FTP exhaust emission tests were conducted. Between each of the tests the vehicle's engine was shut off for approximately 15 minutes. 5 minutes of 50 mph steady-state pre-conditioning was done before the next test was begun.

2.4.3 Fuel Consumption Tests

While driving the 1975 hot-start FTP, the vehicle's fuel consumption was determined by two methods -- (1) direct measurement and (2) calculation. The direct measurement method was a gravimetric weight determination of gasoline used during the test. The calculated fuel consumption was a carbon balance based on the content of the vehicle's exhaust gas.

Table 1 Correlation Test Sequence

	Test Site				
	F	A	C	B	D
Run Number	1[4], 2[1], 3[1], 4[1]	5[2], 6[2], 7[2], 8[2]	9[3], 10, 11, 12	13, 14, 15, 16	17[3], 18, 19, 20
	21, 22, 23, 24[2,3]	25, 26, 27, 28[4]	29, 30, 31, 32[4]	33, 34, 35, 36[4]	37, 38, 39, 40

[1]No measured fuel consumption (FTP-M) data.

[2]No torque measurements.

[3]Omitted from statistical analysis to achieve an equal cell size of 7.

[4]Test not run (ran out of time).

3. Data Analysis

As previously indicated, only seven tests were conducted at test sites A and B. In the statistical analysis, it was desirable to have an equal number of tests at each site. For this reason, one test at each of the remaining sites was randomly omitted (tests 9, 17 and 24).

A one-way analysis of variance (ANOVA) was used on the test data in order to determine if the sites were different in their measurement of HC, CO, CO_2, NOx, calculated fuel consumption (FC-C), measured fuel consumption (FC-M), positive dynamometer torque (+T) and negative dynamometer torque (-T). Scheffe allowances were then calculated so that differences between individual test sites could be determined.

Also a one-way covariance analysis was done with HC, CO, CO_2 NOx, FC-C and FC-M as dependent variables; and barometric pressure (P), dry bulb temperature (DB), humidity (H), +T and -T as random variables. The purpose of this analysis was to determine if the random variables had an effect on emissions and fuel consumption. If certain random variables were found to have a real effect, the data were corrected for this effect and the ANOVA and covariance analysis were repeated.

4. Test Results and Discussion

4.1 Vehicle Emission and Fuel Consumption Tests

Figure 1 through 7 show the composite values of HC, CO, CO_2, NOx, FC-C, FC-M, +T and -T respectively, for each of the 35 tests. Appendix A contains the data for each phase of the tests as well as the composite (the composite is designated as Bag 4).

Table II summarizes the results of the emission, fuel consumption and torque measurements. These are values of the composite emissions.

As earlier mentioned, a one-way analysis of variance (ANOVA) was conducted to see if the test sites measured different levels of emissions, fuel consumption and dynamometer torque. The results of this analysis are shown in Table III. As shown, for all dependent variables, the test sites were different at a high confidence level.

Another question to be answered is which test sites were actually different from each other. To determine this, Scheffe confidence intervals were calculated and the results are shown in Table IV. This table lists the confidence level at which individual test sites differed from each other for each dependent variable. Contrasts which were significant at greater than the 90%, 95% and 99% confidence level are listed. As shown, the variables which differed most significantly between test sites were CO_2, FC-C and +T. As can be expected, there was a close relationship between CO_2 and FC-C. It is interesting to note that sites F and A (which had belt-driven inertia wheel dynamometers) had significantly higher +T than each of the other three test sites (which had direct-drive inertia wheel dynamometers).

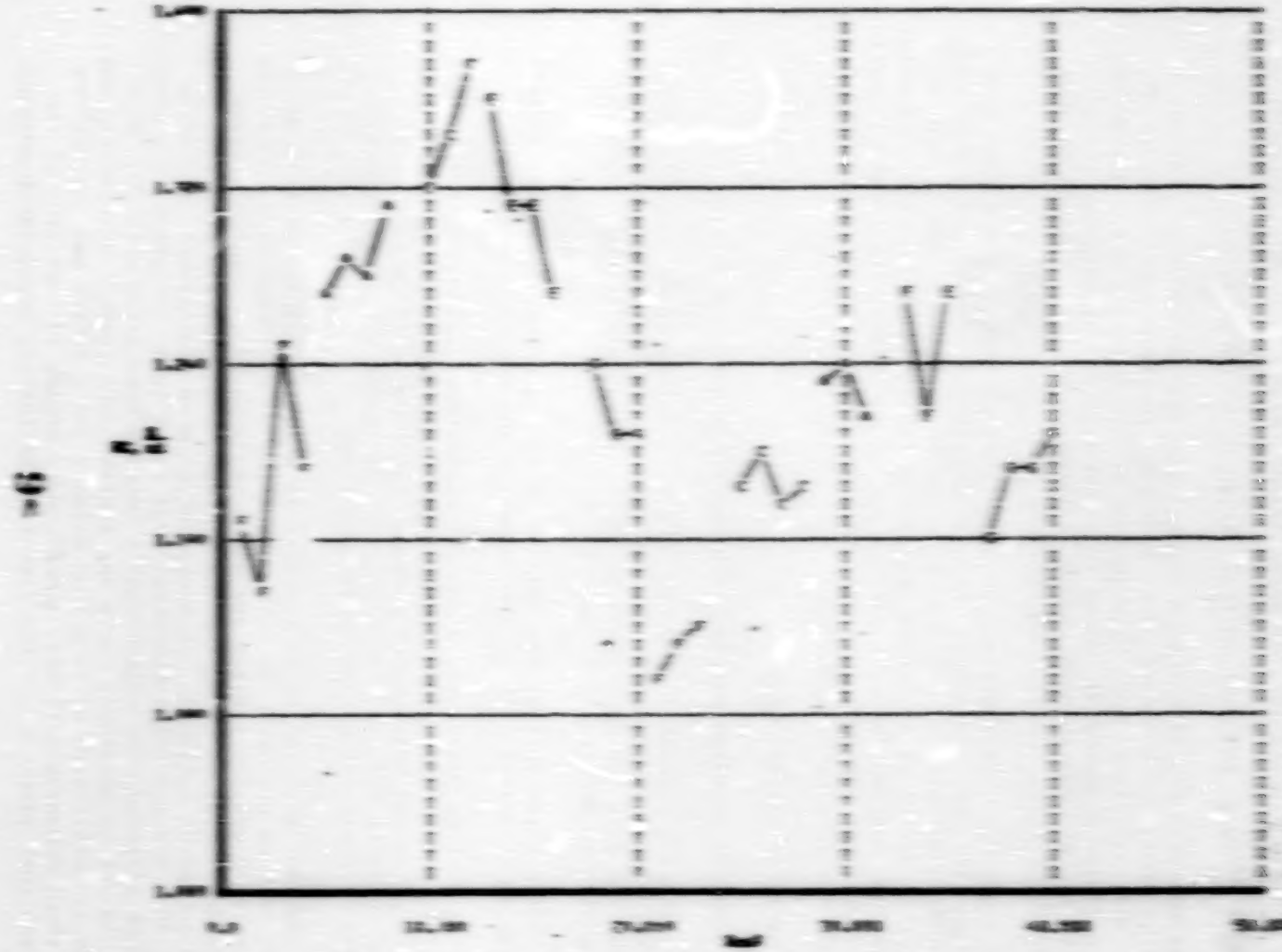
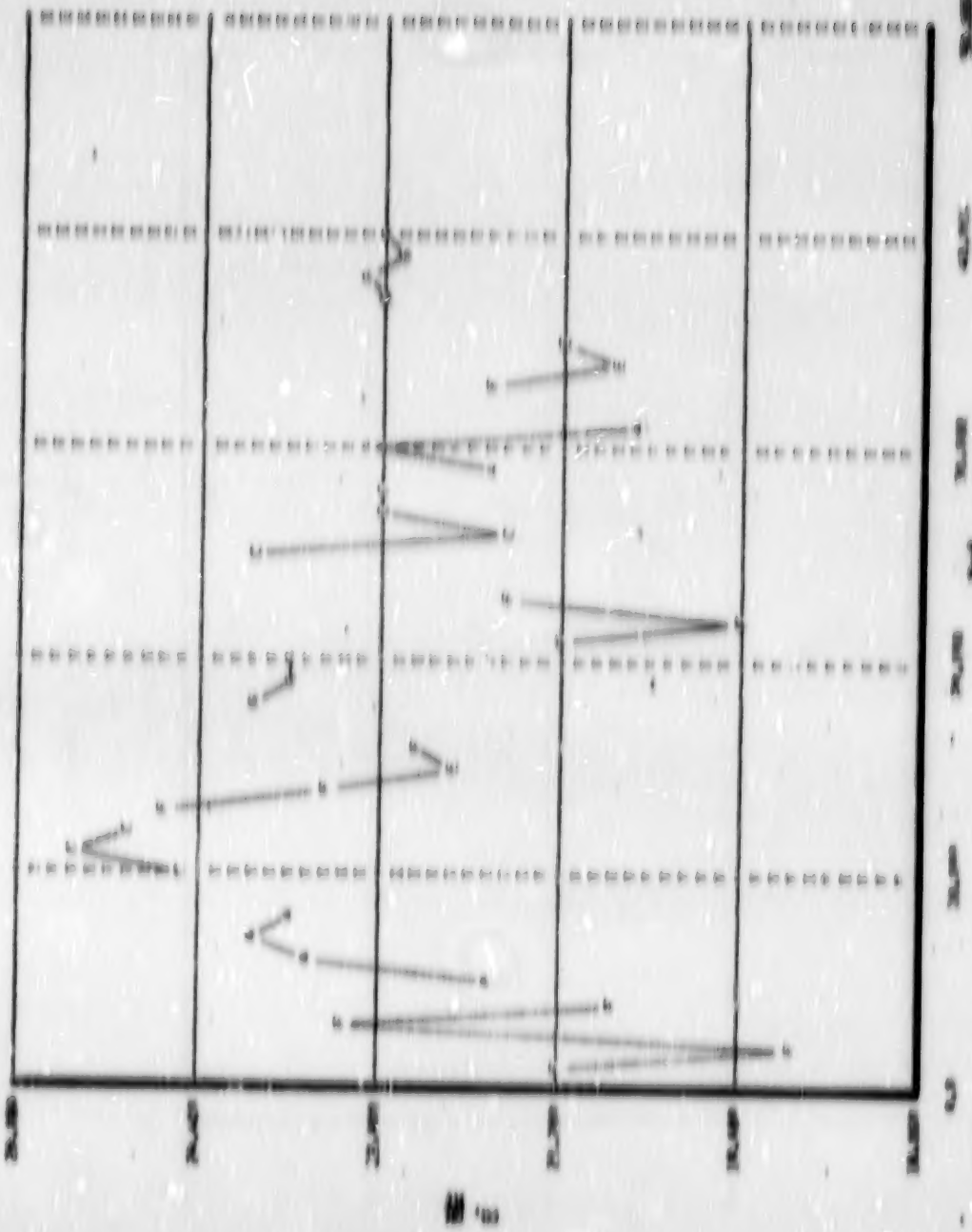
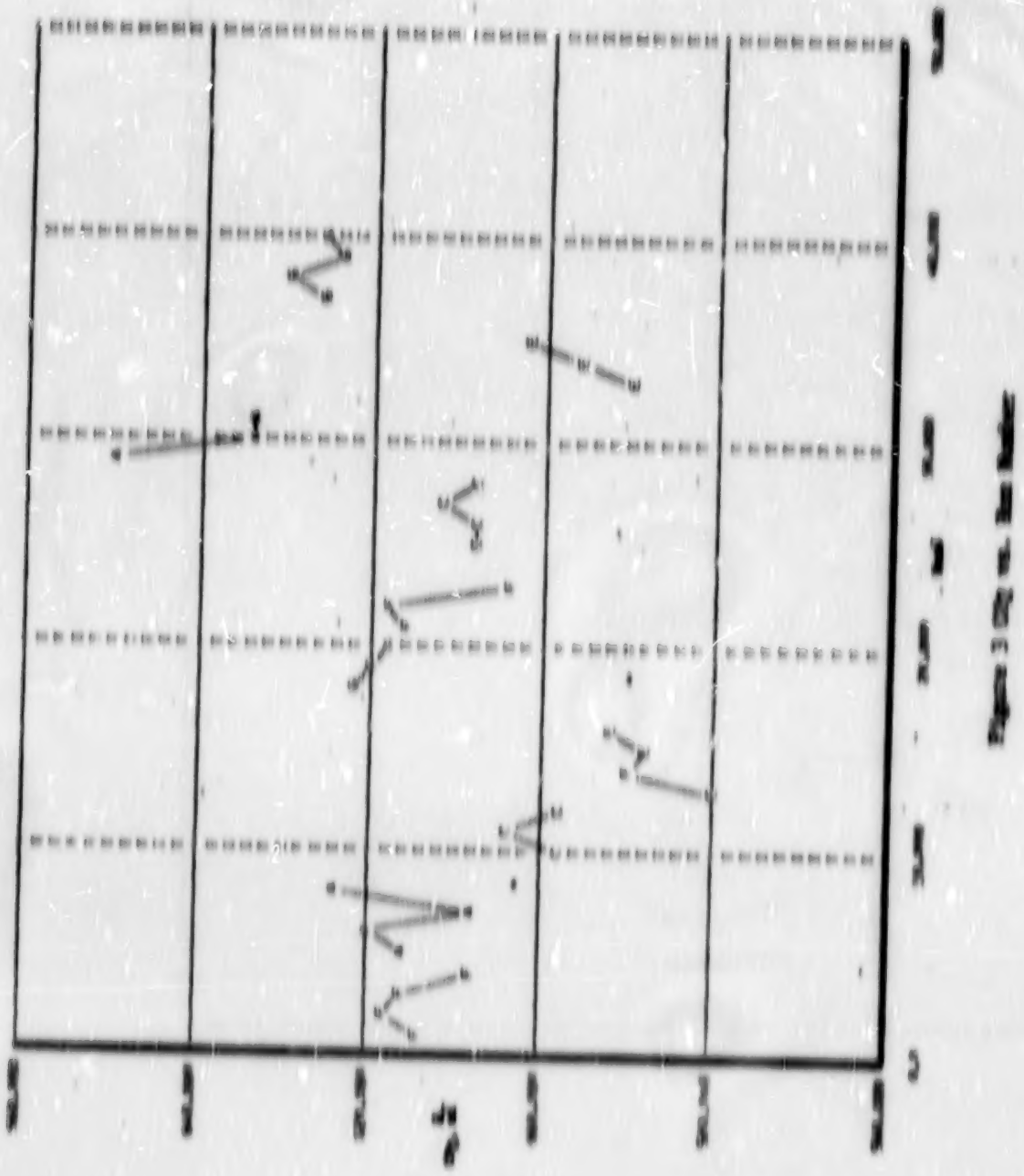
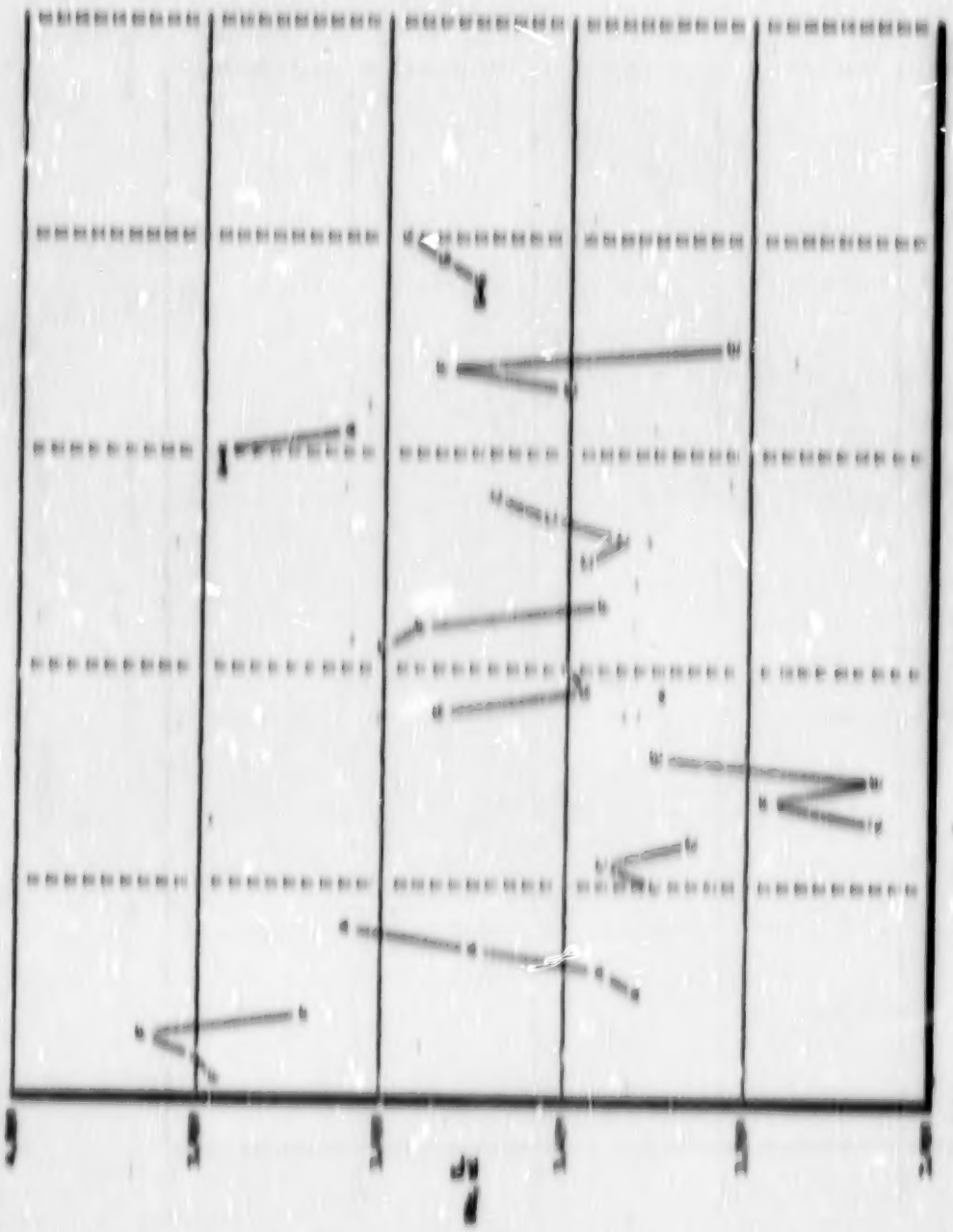


Figure 1 EC vs. Run Number







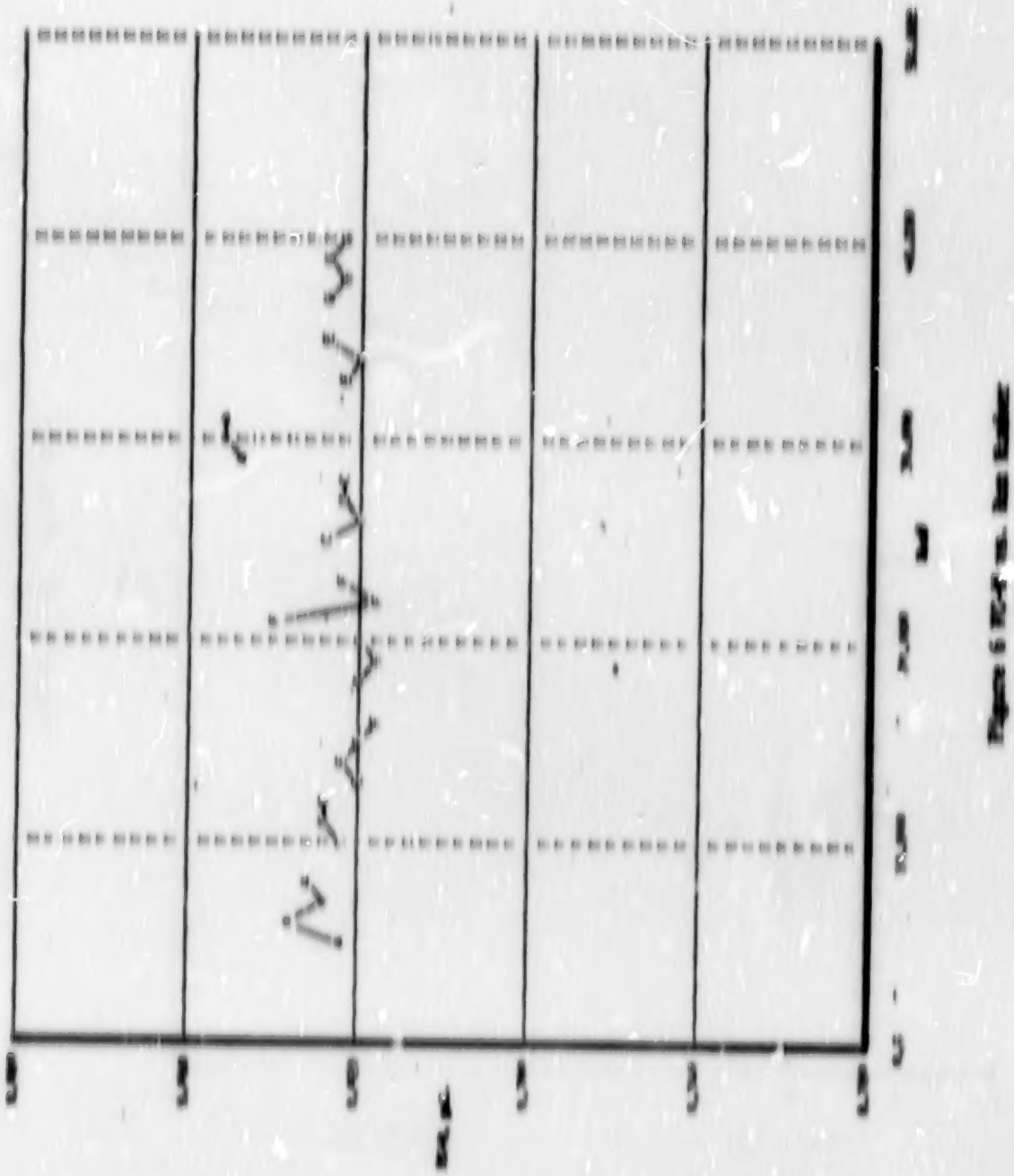


Table 11

Exhaust Emission, Fuel Consumption and Torque Measurement Results for the 1975 Hot-start Procedure

Parameter	Test Site					
	F	A	I	B	H	[illegible]
HC						
Mean, gm/mi	1.158	1.263	1.253	1.287	1.203	1.238
Std. dev., gm/mi	.083	.034	.088	.044	.028	.070
Std. dev., %	4.6	2.7	7.0	3.4	2.3	5.6
CO						
Mean, gm/mi	39.99	39.80	39.78	39.30	35.17	39.32
Std. dev., gm/mi	1.37	1.38	1.39	1.37	.35	1.49
Std. dev., %	3.5	3.4	3.5	3.5	1.0	3.8
CO_2						
Mean, gm/mi	613.3	606.1	606.9	590.8	604.1	611.8
Std. dev., gm/mi	5.6	14.0	5.6	5.5	4.2	13.2
Std. dev., %	0.9	2.3	0.9	1.1	0.7	2.2
NO						
Mean, gm/mi	3.05	3.38	3.36	3.20	3.42	3.47
Std. dev., gm/mi	.17	.19	.07	.17	.07	.20
Std. dev., %	4.7	5.8	2.2	5.4	2.1	5.8
FC-H						
Mean, gal.	0.795	0.809	0.788	0.770	0.810	0.794
Std. dev., gal.	0.0075	0.0170	0.0049	0.0061	0.0037	0.0178
Std. dev., %	0.9	2.1	0.6	0.8	0.5	2.2
FC-M						
Mean, gal.	0.837	0.839	0.825	.823	.826	0.828
Std. dev., gal.	.016	0.0132	0.0029	.0038	.0047	.0094
Std. dev., %	1.9	1.3	0.4	0.5	0.6	1.1
Torque						
Mean, ft-lb-sec	310,570	314,630	296,860	292,340	292,190	297,810
Std. dev. ft-lb-sec	7,041	3,120	5,000	5,330	3,037	5,048
Std. dev., %	2.3	1.0	1.7	1.8	1.0	1.8
-Torque						
Mean, ft-lb-sec	148,190	140,000	141,630	143,100	145,000	144,480
Std. dev., ft-lb-sec	2,289	3,387	2,473	2,897	2,151	3,406
Std. dev., %	1.5	2.4	1.7	2.0	1.4	2.4

Next a one-way covariance analysis was done to determine if temperature, humidity, barometric pressure, and/or dynamometer torque had any real effect on emissions or fuel consumption. Results of this analysis are shown in Table V. Effects are listed which had confidence levels of 80% or greater. The listed coefficient is the best estimate of the magnitude of each effect. Coefficients are based upon data within individual test sites. Plots showing the relationship between these coefficients and the test data at all sites are shown in Figures B-1 through B-17 of Appendix B.

This type of analysis shows that barometric pressure does have a real effect on emissions and fuel consumption. Humidity also demonstrated an effect but at lower levels of confidence. Likewise, -T appears to effect NOx.

Table III

ANOVA results of Composite Emission, Fuel Consumption and Torque Data

Dependent Variable	Mean Square Between Sites	Mean Square Within Site	F-statistic	Confidence Level
HC	.015732	.002833	7.0001	99.99
CO	7.7190	1.4897	5.1815	99.75
CO_2	1301.7	63.314	33.718	>99.99
NOx	.18644	.021374	8.7238	99.99
FC-G	.003064	.000084	34.36	>99.99
FC-H	.000315	.000054	5.833	98.83
+Torque x 10^{-3}	590.60	23.99	24.619	>99.99
-Torque x 10^{-3}	34.65	6.439	5.816	99.98

Table IV

Percent Confidence Level of Contrasts which were significant at greater than the 90% level

Site Contrast		Variable							
		HC	CO	CO_2	NOx	FC-G	FC-H	+Torque	-Torque
F	A	95		90					99
	C	95	99		95			99	99
	E	99		99	99	99		99	95
	G		95			95		99	
A	C			99		99	95	99	
	E		95	99	99	99	99	99	
	G						95	99	
C	E			95		95			
	G			99		99			
E	G	90		99	90	99			

Table V

Random Variables which had an Effect on the Dependent Variables at higher than an 80% Confidence Level. (One-way Covariance Analysis)

Random Variable	Dependent Variable					
	NO	CO	CO_2	NO_x	FO=O	FO=H
Dry Bulb Temp, Conf. Level, & Coefficient				95 0.0250^1		
Humidity Conf. Level, & Coefficient	95 0.00267^2	85 0.0433^2	95 -0.335^2	95 0.00675^2	85 -0.000350^2	95 -0.00711^2
Barometer Conf. Level, & Coefficient	99.9 $-.166^4$	99.9 -3.87^4	99/9 19.3^4	95 0.936^4	99.9 0.0186^5	95 0.00984^5
+Torque Conf. Level, & Coefficient				95 0.60×10^{-6}		94 $.426\times10^{-6}$
-Torque Conf. Level, & Coefficient	97 3.72×10^{-6}					98 $.867\times10^{-6}$

1. g/mi per °F
2. g/mi per gr H_2O / lb dry air
3. gmi per gr H_2O / lb dry air
4. g/mi per in Hg
5. gmi per in Hg
6. g/mi per ft-lb-sec
7. gmi per ft-lb-sec

As a next step in the analysis, the relationships between random and dependent variables found in the convergence analysis were applied to the original test data. That is, the coefficients listed in Table V were used as correction factors and applied to the emission and fuel consumption data. Then a one-way analysis of variance was conducted on the corrected data. A summary of the results of this analysis are listed in Table VI. Also listed in this table are the results of the prior ANOVA on the uncorrected data (previously listed in Table IV).

Table VI

ANOVA Comparison - Uncorrected Data and Data Corrected For Various Random Variables

Type of Analysis	Dependent Variable					
	HC	CO	CO_2	NOx	FC-G	FC-H
Uncorrected Data						
MS Between	.0196	7.72	1502	.186	.00204	.000313
MS Error	.000583	1.40	65.8	.0216	.0000684	.0000354
F-Stat	7.00	5.18	23.7	8.72	44.4	8.83
Conf. Level	99.98	99.73	99.99	99.99	99.99	99.81
Corrected for Temp.						
MS Between				.134		
MS Error				.0207		
F-Stat				6.52		
Conf. Level				99.03		
Corrected for Hum.						
MS Between	.00202	1.22	1483.3	.160	.00202	.000404
MS Error	.000355	1.44	36.6	.0197	.0000680	.0000341
F-Stat	5.68	.849	25.3	8.11	33.3	9.73
Conf. Level	98.10	49.01	99.99	99.98	99.99	99.99
Corrected for Bar.						
MS Between	.0219	4.74	1687	.197	.00283	.000301
MS Error	.000649	.650	37.13	.0178	.0000861	.0000348
F-Stat	30.21	8.78	43.44	11.03	39.60	8.32
Conf. Level	99.99	99.85	99.99	99.99	99.99	99.88
Corrected for +T						
MS Between				.0847		.000177
MS Error				.0158		.0000310
F-Stat				4.09		8.84
Conf. Level				98.90		99.98
Corrected for -T						
MS Between	.0171					.000401
MS Error	.000283					.0000319
F-Stat	8.02					11.6
Conf. Level	99.85					99.99

So Table VI shows the effect of the random variables on the emission and fuel consumption data. "MS (Mean Square) Between" is a measure of the variability between the means of the various test sites. If the "MS Between" is reduced when the data is corrected, this demonstrates that the variability between test sites has been reduced. As shown in Table VI, variability between sites was reduced for each of the emissions when the humidity correction coefficient was applied to the data.

"MS Error" is a measure of the variability of the data within each test site; so a reduction in this quantity indicates that the correction coefficient reduced the scatter in data at individual test sites. As shown in Table VI, application of the correction factors reduced "MS Error" in almost every case. This result is expected since the correction factors are derived from data within test sites.

The F-statistic (F-stat) is the ratio of "MS Mean" to "MS Error", and it determines the confidence level at which we reject the statement that the mean levels observed at each site are equal. Therefore a reduction in "F-stat" means that some of the observed difference between sites was caused by the random variable used in the correction. Table VI indicates that the difference in CO measurements between test sites was because of humidity differences. Humidity also appears to be responsible for much of the differences in the HC measurement. A sizeable reduction in the NOx "F-stat" occurs when the ϕT correction is made.

As was done with the uncorrected data, a covariance analysis was done with the HC, CO and CO_2 data corrected for humidity and the NOx data corrected for ϕT. Results of this analysis are presented in Table VII. As shown, none of the HC or CO contrasts were outside of the 90 percent Scheffe confidence intervals, and the only NOx contrast outside the 90 percent confidence interval was the difference between sites H and G. As had previously been shown in Table IV, several CO_2 contrasts were still statistically significant.

Table VI showed that the only dependent variables which did not show a reduction in "F-stat" were CO_2, FC-C and FC-M. Since it might be expected that ϕT would influence the amount of CO_2, it is instructive to look at a plot of CO_2 vs ϕT (Fig. B-18). This figure shows that the range of ϕT within individual test sites was small as compared to the total range of ϕT measurements. This fact makes it difficult for a covariance analysis to find correlation between CO_2 and ϕT. Figure B-18 also shows the significant difference in CO_2 between site G and sites C and H (as earlier listed in Table IV). If site G were omitted from this figure, the data would show a much stronger relationship, between CO_2 and ϕT (and also between FC-C and ϕT) between test sites.

Table VII

Percent Confidence Level of Contrasts which were Significant at greater than the 90 percent Level -- Data Corrected for Humidity or ΔT as Indicated

Site	Contrast	Exhaust Emission			
		HC Corrected for Humidity	CO Corrected for Humidity	CO_2 Corrected for Humidity	NO_x Corrected for ΔT
F	A			90	
	C				
	B				
	G			90	
A	C				
	B			95	
	G				
C	B			95	
	G				
B	G			99	95

Since the relationship between CO_2 and ΔT is different for site G as compared to the other sites, it is either because site G's CO_2 measurements are large or ΔT measurements are small relative to the other test sites. Figure B-11 indicated that larger ΔT measurements at site G would result in a stronger correlation between HCs and ΔT. For this reason it appears likely that the ΔT measurements at site G were smaller than the true values. On the other hand, the measured fuel consumption at sites G and B were not different, which indicates a problem in the CO_2 measurement. Site G's FC-C measurements were 2.5 percent less than their FC-M values; whereas, site B's and site C's FC-C were 6.4 percent and 4.7 percent, respectively, less than their FC-M values. This indicates that site G's CO_2 measurements are more nearly the correct values.

In summary, the reason for the disagreement in CO_2 values is due to either (or to a combination of) differences in CO_2 or ΔT measurement. The exact reason can not be determined from the data obtained in this program.

5. Conclusions:

1. With the exception of CO_2, this study showed generally good agreement between test sites in the measurement of exhaust emissions.

2. The observed differences in CO measurement were because of humidity differences between test sites.

3. Much of the observed difference in HC measurement were because of humidity differences between test sites.

4. The belt driven dynamometers of site A and F gave significantly higher 4T than the three direct-drive dynamometers.

5. Differences in dynamometer 4T were responsible for much of the difference in NOx measurement between the test sites.

6. Differences in dynamometer 4T did not explain the differences in measured levels of CO_2 and calculated fuel consumption; however, this was partly due to a significant and sizeable difference in CO_2 between sites G and sites C and H. This difference in CO_2 measurement could be explained if the 4T measurements at site G were lower than the true values or if the CO_2 measurements are inaccurate.

7. Barometric pressure had a highly significant effect on all emissions and fuel consumption. However, it did not explain variation between test sites because the test sites differed only slightly in mean barometric pressure.

6. Recommendations

1. Dynamometer type should be standardized to reduce variability between sites, or dynamometer characteristic should be quantitatively identified so the adjustments or corrections can be made.

2. Exhaust emission tests should be conducted at similar humidity conditions to reduce variability.

3. Further investigations are necessary to determine cause of the difference in CO_2 (and therefore calculated fuel consumption) measurement between site G and sites C and H. Similarity of CO_2 analyzer operation should first be checked by using gas cylinder. If there is no difference in CO_2 analyzers, the dynamometers should be checked for a difference in vehicle loading.

7. References

1. Lowery, Richard D., "Emission Laboratory Correlation Study Between EPA and the Motor Vehicle Manufacturers Association of the United States, Inc.," Environmental Protection Agency, Office of Air and Waste Management, Office of Mobile Source Air Pollution Control, Emission Control Technology Division.

8.1 Appendix A - Test Data

Table A-5

DESCRIPTIVE MEASURES STRATUM = 1 Bag #1

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
HC	35	1.1535	.67185 -1	.11676 -1	1.0050	1.3000
CO	35	15.425	1.5168	.25633	11.720	18.670
CO2	35	676.63	17.099	2.8907	641.70	720.80
NOX	35	4.4677	.69211	.11698 -1	3.9600	5.1400
DB	35	76.857	4.0230	.68027	71.000	83.000
BARO	35	29.095	.08511	.14389 -1	28.940	29.320
HUM	35	64.686	20.496	3.4642	9.5000	86.300

DESCRIPTIVE MEASURES STRATUM = 2 Bag #2

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
HC	35	1.2127	.78731 -1	.13309 -1	1.0960	1.3800
CO	35	26.467	1.7566	.29691	24.790	32.470
CO2	35	683.69	17.187	2.9056	614.50	686.10
NOX	35	2.2497	.28856	.48781 -1	1.8600	2.6800
DB	35	76.857	4.0230	.68027	71.000	83.000
BARO	35	29.095	.08511	.14389 -1	28.940	29.320
HUM	35	64.686	20.496	3.4642	9.5000	86.300

DESCRIPTIVE MEASURES STRATUM = 3 Bag #3

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
HC	35	1.2178	.90758 -1	.15342 -1	1.1000	1.5800
CO	35	14.419	1.8483	.31243	11.780	26.810
CO2	35	677.69	16.796	2.8396	643.80	716.30
NOX	35	4.8000	.21747	.36762 -1	4.4600	5.3000
DB	35	76.857	4.0230	.68027	71.000	83.000
BARO	35	29.095	.08511	.14389 -1	28.940	29.320
HUM	35	64.686	20.496	3.4642	9.5000	86.300

DESCRIPTIVE MEASURES STRATUM = A Composite

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
HC	35	1.2321	.67511 -1	.11751 -1	1.1000	1.3700
CO	35	20.571	1.5908	.26884	18.100	24.490
CO2	35	411.82	16.249	2.7776	380.80	449.00

NOX	35	3.4788	.20137	.34038 -1	3.0000	3.9000
DB	35	76.857	4.0230	.68027	71.000	83.000
BARO	35	29.095	.08511	.14389 -1	28.940	29.320
HUM	35	64.686	20.496	3.4642	9.5000	86.300

Table A-6

DESCRIPTIVE MEASURES STRATUM = 1 Composite

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

DESCRIPTIVE MEASURES STRATUM = 1 Bag #1

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

DESCRIPTIVE MEASURES STRATUM = 2 Bag #2

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

DESCRIPTIVE MEASURES STRATUM = 3 Bag #3

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

DESCRIPTIVE MEASURES STRATUM = 4 Bag #4

VARIABLE	N	MEAN	STD DEV	SE OF MEAN	MINIMUM	MAXIMUM
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

8.2 Appendix B - Plots of Emissions and Fuel Consumption Data vs. Random Variables